THE KUIPER BELT

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1, INTRODUCTION

Comets have long been recognized as a very different type of solar system body. Unlike the planets which are all in low eccentricity, nearly co-planar orbits which do not intersect (with one minor exception), cometary orbits are highly eccentric and typically cross the orbits of many of the planets, and tend to be randomly oriented on the celestial sphere. Gravitational encounters with the major planets result in comets being transient members of the planetary system, with typical lifetimes less than 10^6 years. Thus, one of the most fundamental questions about comets has always been, where do they come from?

The comets observed passing through the planetary region are traditionally divided into two classes: long-period (LP) comets with orbital periods > 200 years, and short-period (SP) comets with periods < 200 years. The distinction is largely based on historical attempts to recognize returning comets, and the fact that good orbit determinations only exist for about the past 300 years. The LP comets are typically in very eccentric orbits with semimajor axes up to 105, AU and orbital periods up to 107 years. In addition, their orbits are, to first order, random] y oriented on the celestial sphere, In contrast, the SP comets typically have more modest eccentricities with orbital periods mostly between 5 and 20 years, and are found in low inclination orbits, with i < 35°. The short-period comets also tend to be considerably fainter than their long-period counterparts, and have steeper light curves as a function of heliocentric distance. An excellent review on the basic nature of comets is provided by Marsden and Rocmcr (1982).

The problem of the origin of the long-period comets was solved by Oort (1950), who showed that their source was a vast spherical cloud of comets surrounding the planetary system and extending to interstellar distances. Comets in this cloud, now called the Oort cloud, are only weakly bound to the solar system and are easily perturbed by random passing stars, galactic tides (the non-isotropic gravitational field of the galactic disk), and giant molecular clouds, These perturbation.s scatter the comet orbits in angular momentum (and less so in energy) and cause some to diffuse into the planetary system where they can be observed. The population of the Oort cloud is estimated to be at least 10^{12} comets, possibly 10^{13} (Weissman, 1991) if a proposed unseen inner core of comets in more tightly bound orbits is included (Duncan et al., 1987). The Oort cloud itself is believed to have been populated by icy planetesimals ejected from the outer planets zone during the formation of the planetary system, in particular by Uranus and Neptune. Good reviews on the Oort cloud can be found in Weissman (1991) and Fernandez (1994).

It had generally been thought that the SP comets were simply LP comets that had diffused to short-period orbits by repeated planetary perturbations (Newton, 1893; Everhart, 1972), Oort cloud comets passing through the planetary region for the first time are scattered in orbital energy (proportional to 1/a, where a is the semimajor axis of the orbit), in particular by Jupiter. Comets scattered to larger (hyperbolic) semimajor axes achieve positive energy and are ejected to interstellar space. Comets scattered to smaller orbits return again for another perturbation. In this manner, some small fraction of the long-period comets, typically 10-3 to 10-4 can be brought to short-period orbits after several hundred returns.

Two problems existed with this scenario. First of all, did it achieve the correct number of observed SP comets in the planetary region? Joss (1973) considered the dynamical mechanisms proposed at that time and estimated that there should only be 10-2 SP comets, clear] y in conflict with the then known number of 73 SP comets. However, Delsemme (1973) used different, but still quite reasonable estimates for key parameters such as the cometary lifetime and estimated a population of 84 SP comets, in good agreement with the observations.

The second problem involved the very different inclination distributions of the LP and SP comets. Why were only low inclination 1.1' comets captured to SP orbits. The proposed solution involved the fact that comets in low inclination, direct orbits could make low velocity encounters with Jupiter, resulting in major perturbations. It was believed that these very large perturbations led to the rapid evolution of low inclination LP comets into SP orbits, while higher inclination and retrograde comets with their much smaller planetary perturbations would not evolve far enough in 1/a in their limited physical lifetimes (Everhart, 1972, 1974).

in the late 1970's cometary dynamicists were generally satisfied with this scenario, though there was still much debate about the details, and various researchers tried to model the process more precisely. 1 lowever, a new possibility appeared in 1980 when Fernandez proposed that a far more efficient dynamical source for the SP comets was a belt of remnant icy planetesimals beyond the orbit of Neptune. A distant comet belt at the edge of the planetary system was proposed in a classic paper by Gerard P. Kuiper of the University of Chicago in 1951. Kuiper's paper dealt with the origin of the solar system, and he saw comets as a key to explaining much about the formation of the planetary system. He proposed that comets had formed as icy planetesimals in the outer planets region, and had been ejected to the Oort cloud due to perturbations by Pluto (at that time it was still thought that Pluto was a large planet with a mass of at least several Earth masses), This corrected Oort's misconception that the comets had been ejected from the asteroid belt, Kuiper also proposed that no large planets had accreted beyond Pluto because the long orbital periods at those large solar distances led to very long formation times, greater than the age of the solar system. Thus, there would still be a belt of remnant icy planetesimals there.

Kuiper's suggestion prompted a number of investigations by others into the possibility of an outer planetary system comet belt. However, it was not until almost three decades later that attention would really focus on Kuiper's proposal, and then the attention would come from studies both within and outside our solar system, and on both theoretical and observational grounds, That attention has culminated in the last few years with the discovery of more than a dozen relatively large objects in orbits beyond Neptune, a region now called the Kuiper belt,

Because of its small mass, Pluto cannot significantly perturb the orbits of the icy planetesimals in its zone, and thus Neptune is effectively the outermost planet in the solar system. In fact, Pluto and its satellite Charon are often described as the largest planetesimals to have grown (and still be preserved) in the Kuiper belt, There is currently no evidence for a major planet beyond Pluto (Standish, 1993).

This paper will discuss the several different lines of evidence that came together in the past decade to focus attention on Kuiper's 1951 hypothesis, and the resulting observations and theoretical calculations that have largely confirmed it. Early follow-up on Kuiper's hypothesis will be described in Section 2. The problem of the origin of the short-period comets, which provides key evidence for the existence of the Kuiper belt, will be reviewed in Section 3, Section 4 will discuss additional evidence that comes from studies of protostars and the serendipitous discovery of dust disks around main sequence stars by the IRAS satellite. The observational searches that eventually led to the discovery of Kuiper belt objects, and the nature of the objects found to date will be described in Section S. Dynamical studies of the stability of objects in the outer solar system and in orbits beyond Neptune will be reviewed in Section 6. Finally, implications for future searches and other questions of interest will be discussed in

Section 7.

The course of events leading to the discovery of the Kuiper belt will be presented chronologically, so as to demonstrate how ideas and concepts evolved with time, and how various developments influenced each other. It can be expected that these ideas will continue to evolve and to be refined in the future.

2. OUTER SOLAR SYSTEM PLANETESIMALS

Kuiper (1951) pointed out that the icy composition of comets, proposed the year before by Whipple (1950), could be explained if they formed in the outer solar system, beyond the orbit of Neptune where volatile ices could condense. He hypothesized that Pluto had ejected many of these small icy bodies to distant orbits, in contrast to Oort's (1950) suggestion that the distant comets had come originally from the asteroid belt (Ku iper pointed to the very different composition of comets and asteroids as evidence of their very different formation zones). Kuiper also proposed that planetesimals formed beyond Pluto would not have been ejected and would still reside in a distant belt of comets, just beyond the planetary region,

At that time it was still thought that Pluto was a sizeable planet, with a mass of at least several Earth masses, It was not until the discovery of Pluto's moon Charon in 1979 (Christy and Harrington, 1978) that the mass of Pluto was finally measured and shown to be quite small, ~2.1 x 10-3 Earth masses ($M_{\oplus}$). Pluto is too small to eject or to significantly perturb the orbits of planetesimals in its own zone,

Interestingly, Kuiper was not the first to suggest the existence of a possible comet belt in the outer planets region, A lesser known paper by Edgeworth (1949) also suggested the existence of a residual swarm of "clusters" of material beyond Neptune, By "clusters", Edgeworth meant gravitationally bound swarms of particles, analogous to Lyttleton's (1948) "sandbank" model for cometary nuclei. Edgeworth even suggested that some of the "clusters" may occasional] y detach themselves from the distant belt and be observed as comets, unfortunate] y, Edgeworth's contribution was overlooked until recently, possibly because of its association with the unpopular (and now disproven) sandbank model.

in another study of solar system formation, Cameron (1962) proposed that the protosolar nebula had formed a massive central disk structure extending well beyond the planetary orbits, and that a large number of small bodies existed outside of the planetary system. Whipple (1964) was motivated by Cameron's work to examine the possible perturbat ive effects of a comet belt on the orbit of Neptune, and concluded that a comet belt totaling -10 $M_\oplus$ at 40 AU, or -20 $M_\oplus$ at 50 AU, could better explain the apparent discrepancies in Neptune's motion, than assuming a significant mass for Pluto. Whipple also suggested that material from the trans-Neptunian comet belt could serve as a source for the zodiacal dust cloud, spiraling into the inner solar system due to the Poynting-Robertson effect. It is now recognized that the discrepancies in Neptune's motion are not real (Standish, 1993), but that was not known in 1964.

Whipple's work led Hamid et al. (1968) to study the motion of seven short-period comets with large aphelion distances, in particular comet P/Halley. They concluded that the mass of the comet belt could not exceed 0,5 $M_\oplus$ if the belt was at 40 AU, and 1.3 $M_\oplus$ if it was at 50 AU. Similar results were obtained by Yeomans (1986) in his study of the motion of comet Halley. Anderson and Standish (1986) set an upper limit of <5 $M_\oplus$ on any possible cometary belt at 35 AU, beyond Neptune, based on tracking of the Pioneer 10 spacecraft.

Cameron (1978) considered the physics of a viscous accretion disk formed in the mid-plane of the protosolar nebula and suggested that the disk might grow to 10^3 AU in radius, or larger. He suggested that comets formed in the disk would spiral out to larger orbits as the disk lost mass, and could be pumped to very large orbits if the disk lost a significant fraction of its mass very rapidly, Although Cameron's emphasis was on finding an efficient means for populating the Oort cloud, he did recognize that material would accrete into comets at moderate] y large heliocentric distances beyond the planetary system.

3. ORIGIN OF THE SHORT-PERIOD COMETS

Everhart (1972) showed that the most likely source for the SP comets was LP comets in low inclination orbits with initial perihelia between 4 and 6 AU, close to Jupiter's orbit. Because such comets make frequent close approaches to Jupiter at low relative velocities, they receive particularly large perturbations in energy and can evolve fairly rapidly to short-period orbits, After the comets had evolved to small semimajor axes, additional Jupiter perturbations would reduce their perihelion distances into the terrestrial planets region where they could be observed.

Comets with perihelia closer to the Sun receive lesser perturbations and evolve more slowly, as do comets in high inclination and/or retrograde orbits. The small perihelion comets are also more likely to be subject to physical loss mechanisms such as sublimation and/or random disruption, both induced by solar heating (Weissman, 1980), and thus might be destroyed before they could evolve to SP orbits.

Everhart (1977) later concluded that the number of SP comets could be supplemented by capture of low inclination orbits with perihelia near the other Jovian planets: Saturn, Uranus, and Neptune, Everhart (1974) also suggested that long-lived planetesimals formed inside the orbit of Neptune might serve as a source of SP comets. He thus anticipated, to some extent, the discussions of a distant comet belt that were to become prominent in the following decade.

One problem with Everhart's work was that there did exist some SP comets in high inclination orbits, such as P/Halley with i = 162° and P/Swift-Tuttle with i = 113°. The high inclination SP cornets tend to be in longer period orbits, with 20 < P < 200 years, and are often referred to as "Halley-type" cornets. In contrast, the low inclination SP comets with P < 20 years are often called "Jupiter family" cornets, How were the Halley-type comets captured to SP orbits, given their too small planetary perturbations?

Fernandez (1980) revived interest in Kuiper's (1951) paper by suggesting that a distant belt of remnant, planetesimals, i.e., comets, beyond Neptune, might be the source of the SP comets. Fernandez estimated that a belt of comets between 35 and 50 AU would be -350 times more dynamically efficient than direct capture of long-period comets from the Oort cloud as described by Everhart. The high efficiency is the result of two factors: first, the large planetary perturbations on comets in direct low inclination orbits, and second, the fact that only a very small fraction of the LP comets, whose inclinations are distributed proportional to sin i, are in low inclination orbits, Fernandez suggested that smnc larger objects, on the order of the mass of Ceres, m $\simeq$ 1024 g, had accreted in the comet belt, and that perturbations by these objects resulted in a slow diffusion of belt comets into Neptune-crossing orbits, where they could then begin the evolution to SP orbits.

Hills (1981) speculated on he possible existence of an unseen inner Oort cloud with a population perhaps 10 to 100 times that of the outer, dynamically active Oort cloud. This idea caught on rapidly and it was later shown (Duncan et al., 1987) that a dense inner cloud was the natural byproduct of the ejection of planetesimals from the Uranus-Neptune zone, During the mid 1980's the inner Oort cloud came to be identified also with the proposed comet belt beyond Neptune (Fernandez, 1985a; Weissman, 1985). It was believed that there existed a continuous distribution of comets, extending from just outside Neptune to 5 x 104 AU or more, slowly increasing n mean inclination with heliocentric distance, with the inclinations becoming completely random beyond -104 AU. However, Duncan et al. (1987) showed that comets dynamical y ejected from the Uranus-Neptune region were not "captured" into the inner Oort cloud until they had been pumped up to semimajor axes -3 x 10^3 AU or more, where galactic tidal perturbations could detach their perihelia from the planetary region, i .e., perturb them to perihelia substantially greater than Neptune's semimajor axis. In contrast, the proposed Kuiper belt is a remnant population of icy planetesimals beyond Neptune that accreted *in situ* at their current locations in the ecliptic plane, and have not been significantly perturbed over the history of the solar system. In addition, if we can apply the evidence from observations of protostellar disks and IRAS disks around main sequence stars (see Section 4), the Kuiper belt likely dots not extend beyond about 1-2 x 10^3 AU.

Critical support for Kuiper's (1951) hypothesis came from Duncan et al. (1988) who investigated in detail the two possible dynamical sources for the SP comets: the Oort cloud, and the trans-Neptunian comet belt, Duncan et al. (1988) showed that as Oort cloud comets evolved inward towards SP orbits, they tended to preserve their random inclination distribution. In contrast to Everhart's (1972) earlier results, Duncan et al. found that their dynamical integrations predicted a substantial number of high inclination and retrograde SP comets. Everhart's work apparently failed to produce high inclination SP comets because he did not carry his integrations long enough. Although high inclination and retrograde comets took more returns to evolve to SP orbits because of their smaller mean perturbations, they still would eventually reach small semimajor axes and provide a substantial steady-state population of high inclination and ret regrade SP comets, 'I'his was not observed,

In contrast, when Duncan et al. (1988) started comets from low inclination, low eccentricit y orbits with perihelia near Neptune, they found that they were able to reproduce the low inclination distribution of the observed SP comets, as well as other orbital elements including semimajor axis, aphelion distance, and argument of perihelion (see Figure 1). Duncan et al. (1988) suggested that the trans-Neptunian comet belt would have a population of -4 x 108 comets in order to provide a SP comet resupply rate of 10-2 year-l (Fernandez, 1985b), Duncan et al. also proposed that the trans-Neptunian comet belt should be called the "Kuiper belt. "

Several counter-arguments and criticisms of Duncan et al. (1988) have been proposed (e.g., Stagg and Bailey, 1989). First, Duncan et al. (1988) increased the planetary masses in their integrations by a factor of 40 to speed the dynamical evolution, Although this is a common technique in celestial mechanics, it can lead to spurious results. However, Quinn et al. (1990) repeated the integrations with the planetary enhancement factor reduced to a factor of 10, and obtained similar results. In addition, both Wetherill (1991) and Ip and Fernandez (1991) obtained similar results, each using a simpler Öpik-type Integrator and no enhancement of the planetary masses.

A second counter-argument involves physical loss mechanisms which may preferentially destroy high inclination and retrograde long-period comets during their longer, slower evolution inward from the Oort cloud, Possible loss mechanisms include collisions, sublimation, and random disruption (i. e., splitting). Collision rates are too low to explain the discrepancy, and arc actually higher for direct comets encountering Jupiter and Saturn, because of the very large gravitational cross-sections of those planets at low encounter velocities, Sublimation likely cannot play a significant role because water ice sublimation rates are very low outside ~3 AU (Delsemme and Miller, 1971), at distances which the SP cornets do not approach until late in their dynamical evolution. Sublimation of more volatile ices like CO and H_2CO, and the amorphous-crystalline ice phase transition may provide some mechanism for cometary activity at larger hel iocentric distances, but whether this can lead to nucleus destruction has not been shown , Random disruption is a poorly understood phenomena (Weissman, 1980; Sekanina, 1982) but is' thought to have something to do with heating of the comets as they approach the Sun, and thus, is again likely not applicable to this problem. In addition, Quinn et al. (1990) showed that the Oort cloud still produced an excess of high inclination comets, even if a limiting physical lifetime of 500 or 1,000 returns was assumed for the evolving comets.

Stagg and Bailey (1989) also argued that the inclination distribution is not entirely preserved when LP cornets are evolved to SP orbits. This is, in fact, visible in the results of Duncan et al. (1988) and Quinn et al. (1990) as shown in Figure 2, though an Oort cloud origin still predicts far too many high inclination and retrograde SP comets, However, Stagg and Bailey (1989) failed to examine capture probabilities for inclinations greater than 27°, which is still comparable to the inclinations of the observed SP comets, Thus, their criticism is not supported by their own calculations.

Stagg and Bailey (1989) identified a third possible source of SP comets: comets from the inner Oort cloud thrown back into the planetary region by strong stellar or GMC encounters, and allowed to diffuse down to SP orbits. Since the inner Oort cloud is largely randomized in inclination, the evolution of these comets would be similar to those from the dynamically active outer Oort cloud, and they would thus again produce an excess of high inclination and retrograde comets; this was demonstrated by Quinn et al. (1990). However, this is a possible dynamical path for creating Halley-type comets and should not be ignored in future dynamical studies.

Additional understanding of the dynamical evolution of SP comets was provided by Levison and Duncan (1994). They performed long-term integrations of the orbits of all the known SP comets and showed that a better parameter for denoting the difference between Jupiter family and Halley-type comets is the Tisserand parameter

$$T = a_J/a + 2\sqrt{(a/a_J)\,(1-e^2)}\,\cos i \qquad (1)$$

where a, is’ the semimajor axis of Jupiter’s orbit, and a, e, and i are the semimajor axis, eccentricit y and inclination of the comet’s orbit. T is an approximate constant of the motion in the restricted 3-bed y problem (Sun-Jupiter-comet) and was devised to identify returning SP comets, even if their orbits had been significantly perturbed by Jupiter. Levison and Duncan (1994) suggested that Jupiter family comets have values of $T > 2$, and Halley type comets have $T < 2$. Using this definition, they showed that relatively few comets changed family or type during their dynamical evolution in the planetary system,

It is then possible to explain the Jupiter family and Halley-type cornets if the observed SP comets arc a mix of comets from the two dynamical reservoirs, the Oort cloud and the Kuiper belt. The low inclination SP comets with $T > 2$ come primarily from the low inclination Kuiper belt, while the high inclination Halley-type comets with $T < 2$ come primarily from the random inclination Oort cloud. Given the relative numbers in the two families, the Kuiper belt appears to be the dominant source of the observed SP comets. However, observational selection effects make it more difficult to find Halley-type comets, and thus we cannot yet obtain the exact proportion between the two families, An as yet unanswered question is what stops Oort cloud comets from evolving to shorter period orbits, with $P < 20$ years?

4. PROTOSTELLAR AND STELLAR DISKS

One of the many surprising discoveries of the Infrared Astronomical Satellite (IRAS) mission was the detection of extended dust disks around main sequence stars, including Vega (α Lyrae), Fomalhaut (α Piscis Austrini), β Pictoris, and ϵ Eridani (Aumann et al,, 1984, Gillett, 1986). The discovery was made quite by accident when the IRAS science team attempted to use Vega as a cal ibrat ion source and discovered substantial infrared excesses at wavelengths of 60 and 100 μm. Subsequent studies (Backman and Gillett, 1987; Aumann and Good, 1990) found infrared excesses around many main sequence stars, including solar type stars.

in a few cases, IRAS data was able to resolve the excess emission and show that it came from flattened, or disk-like sources. The disk-like structure was dramatically illustrated by coronagraphic images of the β Pictoris disk which is viewed nearly edge on (Smith and Terrile, 1984, 1987) and is shown in Figure 3. The disk brightness declines approximately as $r^{-1.7}$, and extends up to 1,100 AU from the central star. Estimates of the masses of the material in the disks range from a tiny fraction of an Earth mass, if all the material is just in micron-sized particles, to hundreds of Earth masses, if the material has a typical asteroidal/meteoroid size distribution and extends up to bodies 10^3 km in diameter (Gillett, 1986), An interesting feature of the IRAS dust disks is that they do not extend all the way in to the central star. Maximum temperatures observed by IRAS show that the disks are cleared out to distances ranging from 20 to 70 AU around the four stars listed above. It was suggested that these clearings are due to sweep-up of material by planetary formation processes,

Another interesting feature is that the expected lifetimes of the dust in the disks is less than the age of any of the stars. Dust is removed by radiation pressure, Poynting-Robertson effect, and collisions, Thus, there must be some mechanism replenishing the material in the dust disks.

Weissman (1984) and Harper et al. (1984) first suggested that the IRAS dust disks were composed of comets, and that collisions and sublimation of volatile ices were continuously resupplying the fine material in the dust clouds. Weissman proposed that the disks were primordial inner Oort clouds which had not yet been dispersed to larger semimajor axes and random inclination orbits. An additional link to comets was provided by observations of the β Pictoris disk by Telesco and Knacke (1991), They detected the 10 μm silicate emission feature which is also seen in cometary comae and in dense interstellar dust clouds.

Aumann and Good (1990) pointed out that since IRAS dust disks were common around G type stars like the Sun, it would be unusual if the Sun did not possess a similar disk. They showed that if the solar system was surrounded by a disk as massive as that around β Pictoris, it could neither be confirmed nor ruled out by IRAS observations, which are dominated in the ccl ipt ic by warm emission from the zodiacal cloud in the planetary region,

Another astrophysical data source on the existence of circumstellar disks are observations of accretion disks around forming protostars. Although such disks were long suspected on theoretical grounds (Lynden-Bell and Pringle, 1974), their existence was not really established until the late 1980's when observational tools became good enough to detect them. Sargent and Beckwith (1987) mapped emission at millimeter wavelengths around the protostar HL Tau and showed that it was a disk-like structure extending out 2,000 AU from the protostar, and orbiting the protostar at Keplerian velocities. The mass of the disk was estimated at -0.1 $M_\odot$. Since then, disk-like structures have been imaged at millimeter wavelengths around many protostars, with mass estimates between -0.001 and 0,1 $M_\odot$,

Another method for detecting protostar disks has been to look for infrared excesses in IRAS data. Surveys of the IRAS Point-Source Catalog (Cohen et al., 1989; Kenyon et al., 1990) showed disks around 25% to 50% of protostars. Millimeter surveys of many of the same stars showed that many had disk structures, even in cases where they had not been detected at infrared wavelengths (Beckwith et al,, 1990). This suggests that the particle size distribution in the disks may be evolving as fine material is either swept up or blown away.

5. OBSERVATIONAL SEARCHES OF THE OUTER SOLAR SYSTEM

The most complete search for trans-Neptunian objects is that by Tombaugh (1961) which covered the entire sky north of -30° declination to B magnitude 16, and succeeded in discovering Pluto in 1930. in addition, Tombaugh searched 1,530 square degrees of sky to a limiting V magnitude of 17.5. No outer solar system objects other [ban Pluto were found. Luu and Jewitt (1988) searched 200 deg^2 photographically with a Schmidt telescope to a limit of V = 20, and 0.34 deg^2 with a CCD camera to R = 24 (V $\simeq$ 24.5), both with negative results. Levison and Duncan (1990) searched 4.9 deg^2 using a CCD to V = 22,5, again with negative results. Other negative searches include Cochran et al. (1991) and Tyson et al. (1992).

Kowal (1989) searched 6,400 deg^2 photographically to approximately V = 20, discovering the first outer solar system planet-crossing object (other than Pluto and recognized comets) 2060 Chiron. Chiron is Saturn-crossing with a perihelion of 8.47 AU and an aphelion of 19,03 AU, just inside the orbit of Uranus, Its expected dynamical lifetime in this orbit is about 2 x 10^6 years, and there is a good possibility of it being perturbed into an orbit with its perihelion in the terrestrial planets region during its lifetime (Hahn and Bailey, 1990), Chiron displays comet-like outbursts and coma (Meech and Belton, 1989; Bus et al,, 1991). It was suggested early on that Chiron might be a surviving planetesimal from the Uranus-Neptune zone (Weissman, 1985) where dynamical lifetimes are on the order of 10^8 years or more (Wetherill, 1975),

Two additional outer solar system, planet-crossing objects have also been discovered: 5145 Pholus (a = 20.4 AU, e = 0.574), and 1993 HA_2 (a = 24.8 AU, e = 0,523),[1] Both of these objects are in chaotic, unstable orbits with aphelia beyond Neptune, and with dynamical lifetimes of 10^6 to 108 years, All three objects, Chiron, Pholus, and 1993 HA_2 must have come from some longer-lived dynamical reservoir, The maximum inclination among the three is 24.69° for 5145 Pholus, suggesting that their source reservoir is likely in the ecliptic plane, and may be the same as that for the low inclination S1' comets,

'l'he first successful detection of an object beyond the orbit of Neptune (other than Pluto and Charon) was by Jewitt and Luu (1992, 1993a). Using a CCD camera on the 2.2 meter university of Hawaii telescope, they searched -1 deg^2 to V = 25 and found object 1992 QB,

[1] A fourth object, 1994 TA, has been discovered at a heliocentric distance of 15.08 AU, but its orbit is not yet determined (Chen et al., 1994. Min. Plan. Met. Circ. 1994 -T01).

in August 1992, at a heliocentric distance of -41.2 AU. The object was magnitude R = 22.8 and reddish in color, with V - R = 0,7 ± 0.2. If the object has a typical cometary albedo of 0,04, then it is -250 km in diameter. Subsequent observations allowed Marsden (1993a) to determine an orbit for 1992 QB$_1$ with semimajor axis of 43.82 AU, eccentricity of 0.0876, inclination of 2.210, and orbital period of 290.2 years. The perihelion distance of 39.99 AU is well beyond the orbit of Neptune; the aphelion of 47.67 AU is about 2 AU inside the aphelion distance of Pluto, Dynamical investigations (see next section) suggest that orbits like that of 1992 QB$_1$ are stable over the history of the solar system,

The second discovery of a trans-Neptunian object, designated 1993 FW, was by Luu and Jewitt (1993a) who found an R = 22.8 magnitude object at 42.1 AU. 1993 FW is similar in size to 1992 QB$_1$ (possibly slightly larger) but less red in color with V - R = 0.4 ± 0.1, A subsequent orbit solution by Marsden (1993b) found a = 43.93 AU, e = 0.0407, i = 7.74°, and P = 291.2 years. Again, this orbit would be expected to be stable over the history of the solar system ,

The next four objects discovered were significantly different in that their heliocentric distances were substantially closer to Neptune, in a region where the orbits would not be stable unless protected by some dynamical mechanism, The four objects: 1993 RO (Jewitt and Luu, 1993b), 1993 RP (Luu and Jewitt, 1993b), 1993 SB and 1993 SC (Williams et al. 1993) were found at heliocentric distances ranging from 32.3 to 35.4 AU. Interestingly, all four objects were approximately 60° from Neptune in the sky, suggesting a possible Trojan-type dynamical relationship. However, Marsden (1994) has preferred an orbit solution for all four objects as being in a 2:3 mean-motion resonance with Neptune, similar to the motion of Pluto. For the moment, such orbital solutions should be considered as tentative, as there are insufficient observations to clearl y define the motion of these objects, Assuming a cometary albedo, these first four trans-Neptunian objects range between -90 and -290 km in diameter.

Continued searches have now discovered a total of 17 trans-Neptunian objects, which are listed in Table 1, in order of discovery. ‘I’he columns in the table are the heliocentric distance at discovery, the semimajor axis and eccentricity (if a suitable orbit solution exists), the orbital inclination, the orbital period, the R magnitude at discovery, and an estimated diameter, based on an assumed cometary albedo of 0.04. Eight of the discovered objects are at heliocentric distances where they might make close approaches to Neptune, unless protected by some dynamical mechanism, The other nine objects are well beyond the orbit of Neptune, though the eccentricity of their orbits are only well determined in two cases so far.

The largest object appears to be 1993 SC at a diameter of -290 km, with 1993 FW, . . 1994 JQ_1, and 1994 TB, close behind at -270 km diameter (assuming an albedo of 0.04). ‘I’he smallest is 1993 RP at -90 km. The cumulative absolute magnitude distribution of the 17 objects is shown in Figure 4. The very steep slope of the distribution between absolute R magnitude 6.4 and 7.0 is much greater than that observed for the collisionally evolved main asteroid belt. The steep slope may be indicative of an upper size limit in the growth of bodies by accretion in the Kuiper belt. However, given the small number of bodies discovered at this time, this cannot be considered a very robust conclusion. The low slope of the diagram at diameters less than 200 km (absolute magnitude > 7.2) is indicative of observational incompleteness at the fainter magnitudes,

Jewitt and Luu (1994) estimated that there are 3.5 x 104 objects in the Kuiper belt larger than 100 km diameter, based on the discovery of their first 7 objects after searching a total of -1.2 deg^2, and assuming that the belt was confined to orbital inclinations less than -16°. If each of the objects is 100 km in diameter with a density of 1.0 g/cm^3, then the minimum mass of the Kuiper belt is -1.8 x 10^{2s} g, or -0,003 $M_{\oplus}$, Jewitt and Luu (1994) also noted that past observational searches set an upper diameter limit of 600 km on comets between 30 and 50 AU.

6. DYNAMICAL STABILITY IN THE OUTER PLANETS REGION

Study of the long-term dynamical evolution of the orbits of objects in the outer planetary region has been made possible in the past decade as a result of improved integration codes developed to study the problem, and the availability of high-speed, low-cost computer workstations which can be dedicated for periods of weeks or months to a single dynamical investigation. The first detailed study of the stability of orbits in the Kuiper belt was by Torbett (1989), who showed that low inclination orbits beyond Neptune would be chaotic and could become Neptune-crossing if their perihelion distances were between 30 and 45 AU. Torbett also estimated that the population of the Kuiper belt was on the order of 10^9 comets in order to provide a resupply rate of short-period comets of 10-2 year^{-1} (Fernandez, 1985b). Torbett and Smoluchowski (1990) showed that the chaotic motion induced by planetary perturbations could also scatter Kuiper belt comets to larger perihelia and semimajor axes.

Glad man and Duncan (1990) followed the evolution of test particles in initially near-circular orbits throughout the outer planets region for 2.2 x 107 years, and showed that most orbits between the four giant planets become planet-crossing in 10S to 10^7 years. Once the orbits are planet-crossing, they will fairly rapidly be ejected from the planetary region. However, Gladman and Duncan found that orbits beyond a = 34 AU were stable for the duration of their integrations.

Holman and Wisdom (1993) performed similar integration but for a duration of up to 8×10^8 years for test particles between the giant planets, and 2×10^8 years beyond Neptune, Their results are illustrated in Figure 5. Particularly long-lived objects near the semi major axes of each of the giant planets are 1:1 Trojan-type librators near the L_4 and L_5 Lagrange points, 60° ahead and behind each planet in its orbit, Long-lived stable regions in the Kuiper belt were found between 37 and 39 AU, and beyond -42 AU.

Even longer simulations were performed by Levison and Duncan (1993) who integrated the orbits of test particles in low eccentricity orbits between 30 and 50 AU for 109 years. Their results are shown in Figure 6. For initially near-circular orbits (e = 0.01), stable regions exist with semimajor axes as close as 34 AU from the Sun, though some objects were lost as far out as 40 AU. For modest eccentricity orbits (e = 0. 10), the stable regions between 35 and 42 AU were considerably narrower, but most orbits beyond semimajor axes of 42 AU survived for the full 10^9 years of the integration. Some of the apparently stable regions between 34 and 40 AU may be associated with mean-motion and/or secular resonances with Neptune.

For yet higher eccentricities, up to e = 0.2, Levison and Duncan (1993) found that objects were lost from the Kuiper belt with semimajor axes as large as 46 AU. In addition, it was found that semimajor axes near 48 AU tended to be unstable; these orbits are close to the 2:1 mean-motion resonance with Neptune.

Levison and Duncan (personal communication) have now extended their integrations of Kuiper belt test particles to periods of 4×10^9 years, essentially the age of the solar system. For low inclination orbits (i = 1°), stable orbits are generally found between semimajor axes of ~37 and 40 AU and beyond -42 AU for e = 0.01; between -38 and 39 AU and beyond

~43 AU fore = 0.05; beyond -44 AU fore = 0.10; and beyond ~46 AU for e = 0.15 (except for orbits near the 2:1 resonance with Neptune). The detailed structure of the stable and unstable regions is quite complex. For orbits with initially higher inclinations, the structure is even more complex, though again, stable regions generally exist for semimajor axes greater than 43 AU, for eccentricities <0.10.

Based on these integrations, the orbits of 1992 QB_1 and 1993 FW, described in the previous section, are likely stable over the age of the solar system. The long-term stability of the other objects at r > 40 AU will depend on their orbital eccentricities when they arc determined; most will be stable if their orbital eccentricities are suitably low, <0.1.

Presumably, the region beyond Neptune was once populated by a continuous distribution of icy planetesimals. That region has now been shaped dynamically by Neptune perturbations, so as to give a complex structure similar to that seen in the main asteroid belt, where secular and mean-motion resonances have played a major role in clearing specific areas of (a, e, i) space. An example of this is shown in Figure 7 (Levison and Duncan, personal communicant ion), which gives the radial distribution of comets in the Kuiper belt after 4 x 10^9 years, The initial distribution of objects is given by a 1 /r^2 surface density distribution in the protosolar nebula, and an initial eccentricity of 0.05 is assumed, The trans-Neptunian region is largely depleted at r < 33 AU, whereas the Kuiper belt population is relatively untouched at r > 46 AU.

Levison and Duncan (1994) showed that the resupply rate of SP comets must be -O. 006 year^{-1} to maintain the currents eady-state population, somewhat higher than Fernandez's (1985b) earlier estimate of 0,01 year-l. New studies of the rate of comets currently leaving the Kuiper belt for Neptune-crossing orbits give a loss rate of 6 x 10^{-11} year^{-1} (Levison and Duncan, personal communication), of which -17% are expected to successfully evolve to visible SP comets (Duncan et al., 1988). This then suggests a current population for the dynamical y active region of the Kuiper belt between 34 and 46 AU of 6 x 10^9 comets. If these comets have a typical mass equivalent to the mean mass of 3.8 x 10^{16} g estimated by Weissman (1990), then the total mass of the dynamically active region of the Kuiper belt is 2.3 x 10^{26} g or 0.04 $M_\oplus$. 'l'his is consistent with the mass limits noted in Section 2.

At heliocentric distances > 46 AU, the Kuiper belt consists of a population of icy planetesimals that have orbited essentially undisturbed since the origin of the planetary system. This dynamically inactive region may extend 1-2 x 10^3 AU from the Sun, and may contain several hundreds of Earth masses of material, suggesting a population of between 10^{13} and 10^{14} comets. Thus, the Kuiper belt may contain even more comets than the Oort cloud.

7. DISCUSSION

The past two decades have brought about a remarkable convergence of theory and observations, both inside our solar system and of nearby stars and protostars, which suggests that disks of planetesimals extending out hundreds to thousands of AU from the central star arc ubiquitous. The total mass in each disk may amount to tens or hundreds of Earth masses, a significant fraction of the total mass of the known planetary system, which is -450 $M_\oplus$).

The evidence for the existence of the Kuiper belt is compelling. It has been shown that the orbital element distributions of the Jupiter family comets can only be explained if they come from a highly flattened source in the ecliptic plane. Although legitimate questions were raised concerning Duncan et al.'s (1988) original paper, most of those objections were answered by Quinn et al. (1990). In addition, new integrations by Levison and Duncan (personal communication) are now underway and are again confirming the results of Duncan et al. (1988) and Quinn et al. (1990), with no enhancement of the planetary masses.

Observations of dust disks around protostars and main sequence stars demonstrate that structures like the Ku iper belt are a common feature of star formation. It is somewhat amusing that we can observe these disks around other stellar systems but not yet around our own, a case of not being able to see the forest for the t recs. However, future infrared surveys hold the potential of much greater sensitivity, and the ability to look for the Kuiper belt, now that we know that it is likely there.

The discovery of comets beyond Neptune in orbits where they are likely stable over the lifetime of the solar system is further confirmation of the existence of the Kuiper belt. Given the small area searched to date, and the limiting magnitudes of the surveys, it can be expected that future searches will be increasingly successful at finding more Kuiper belt objects.

The discovery of objects at trans-Neptunian distances appears to be accelerating, with 1 found in 1992, 5 found in 1993, and 11 so far in the first 10 months of 1994. When the first asteroid, Ceres, was discovered in 1801, it was followed by three discoveries in the next six years, but then none for 38 years until the introduction of astronomical photography. As with the asteroids, the discovery of Kuiper belt objects appears to be closely associated with an enabling technology, the application of large area CCD's to astronomical searches. Further developments such as arrayed CCD focal planes and automated search programs should further accelerate the discovery rate in the near future.

Current ground-based limits on the searches for Kuiper belt objects have been reported to be R magnitude 25 (Jewitt and Luu, 1994). However, only two objects have been discovered at R > 24, and only five at R > 23. The bulk of the discoveries have come in a fairly narrow range of magnitudes, between R = 21.5 and 23, This is dramatically illustrated by the steep slope in Figure 4. If searches did really extend to R magnitude 25, we would expect the discovery of far more objects in the 50-200 km diameter range. Thus, the practical limit of the ground-based searches at present is R = 23, except for a few fortunate fainter discoveries.

The existence of a large number of fainter comets in the Kuiper belt seems inescapable. Modeling of the accretion of icy planetesimals in the Neptune zone by Greenberg et al, (1984) showed that large bodies would accrete up to dimensions of 250-1000 km, with a few bodies undergoing runaway accretion to larger sizes, including one which would form the core of Neptune. Greenberg et al, (1984) found that the slope of the expected size distribution at diameters larger than 16 km was quite steep, qualitatively similar to that in Figure 3, but more modest at smaller sizes.

The same dual-slope power law distribution was found by Everhart (1967) who determined the intrinsic brightness distribution for LP comets as a function of their absolute total magnitude (including coma), including correction for observational selection effects. Weissman (1 990) scaled Everhart's results to obtain a dual-slope power law size distribution for cometary nuclei. This distribution has the interesting quality that the majority of the integrated mass of the distribution comes from the bodies at the junction of the two slopes, at diameters between 2 and 32 km.

It would be expected that the size distribution of LP comets formed in the Uranus-Neptune zone and Kuiper belt comets formed just beyond that, are similar. Accretion of LP comets into larger bodies would proceed more rapidly at the shorter orbital periods in the

Uranus-Neptun ezone, but that process would be truncated by their ejection to the Oort cloud. Kuiper belt comets would accrete more slowly in their more distant orbits, but would have the entire history of the solar system to achieve their current size distribution, Unfortunately, detailed direct measurements of the sizes of LP and SP comet nuclei are not yet sufficient to determine their respective size distributions or to discriminate between the two dynamical types.

The accretion of even larger objects in the Uranus-Neptune zone and in the Kuiper belt has been speculated on by Stern (1991) who suggested that 102 to 10^3 1000-km diameter (or larger) objects may have accreted, Neptune's retrograde satellite Triton is proposed as one member of this class of objects still resident in the planetary system. Other large objects may have been ejected to the Oort cloud, or may be resident in the stable regions of the Kuiper belt at a > 46 AU, However, if several of these objects did exist as close as 50 AU, it is surprising that none were detected by Kowal's (1989) extensive photographic search between 1976 and 1985.

Limits placed on the sky density of Kuiper belt objects versus magnitude by the various searches to date are shown in Figure 8 (Levison, personal communication), along with a star indicating the discovery of 1982 QB_1. The dashed lines are power law fits to the diameters of Kuiper belt objects. Asteroids have a typical slope parameter, $b_2 = 3,5$, which puts most of the mass in the largest bodies. However, the surveys of Kowal (1989) and Cochran et al. (1991) appear to rule out such a slope, and suggest that a steeper slope, possibly $b_2 = 5$, might be a better fit, However, the discussion above with regard to the real effective magnitude limits of the searches to date, suggests that some if not all of the points in Figure 8 should be shifted to the left to lower magnitudes, which would then still leave considerable uncertainty about the actual size distribution of the Kuiper belt objects, in addition to ground-based searches of the outer solar system, the repaired 1 Iubble Space Telescope is now also being used to look for Kuiper belt objects. Search fields were exposed and are now undergoing analysis by Cochran, Levison, Stern and Duncan (personal communication). It is anticipated that the HST images with the new WFPC 2 camera can reach magnitude 28,5, equivalent to a 20 km diameter comet at 40 AU, or 30 km diameter at 50 AU, assuming an albedo of 0.04 (solid circle in Figure 8).

An alternative means of searching for the Kuiper belt is to look for the possible gravitational effects on spacecraft transitioning the region. The Voyager 1 and 2, and Pioneer 10 and 11 spacecraft are currently at heliocentric distances between -38 and 60 AU, ranging from the inner edge of the dynamically active Kuiper belt to the dynamically stable region. The spacecraft are moving outward at velocities of 2.5 to 3.5 AU year-l. However, the trajectories are generally not in the ecliptic plane. In addition, the Voyager spacecraft use thrusters to maintain attitude control, which degrades their ability to measure small gravitational accelerations. Nevertheless, it will be interesting to see if these spacecraft can provide any evidence for the existence of the Kuiper belt, The Voyager 1 and 2 spacecraft could conceivably operate until about the year 2018, when they would be at 139 and 116 AU, respectively.

It is not yet clear whether the difference in the heliocentric distances of the formation zones for the LP and SP comets would manifest itself in recognizable compositional and/or physical differences in the LP and SP comets. 'l'he temperature gradient in the solar nebula can be expected to vary slowly, approximately as $r^{-1/2}$. Current maximum blackbod y temperatures are typically -88 K at 20 AU, versus 63 K at 40 AU. This difference may be reflected in the volatile ices, such as CO, HCN, CH_4, and NH_3 frozen into cometary nuclei. Systematic depletions of some comets in C^2 have been identified, but the reason for these depletions and any possibly dynamical correlations arc not yet clear,

There is an ongoing debate whether the objects in the Kuiper belt should be regarded as comets or asteroids (or perhaps be given some other classification). Because the objects have not displayed any evidence of cometary activity at discovery, in particular a cometary dust coma, they have been given asteroidal designations, On the other hand, given their location in the outer solar system and the likel y fact that they formed at those large solar distances, the objects almost certainly contain large quantities of water and other volatile ices, In addition, given their relatively small sizes, they probably are largely unprocessed solar nebula condensates. If these objects were brought to small heliocentric distances, their ices would sublimate and they would appear as comets. In fact, that is precisely the conclusion that has been reached with regard to the Kuiper belt; it is the source of a substantial fraction of the observed SP cornets. Thus, the objects in the Kuiper belt are comets, and probably should be given cometary designations.

The very slow heliocentric motion of objects in the Kuiper belt requires repeated astrometric observations over a period of many years to establish good orbital solutions for each object. Observers are encouraged to support such programs so that the radial distribution and orbital statistics of the Kuiper belt can be established, and in order to discriminate between different possible dynamical resonances with Neptune,

Another question concerns whether Kuiper should share credit for the suggestion of the belt's existence with K. E. Edgeworth. Both of them clearly suggested the existence of small objects orbiting the Sun beyond the orbit of Neptune, and Edgeworth (1949) went a step further to suggest that these objects may occasionally appear as visible cornets. It would seem that credit should be shared. However, the term "Kuiper belt" has already been in use for several years now, and it may be confusing to try and change it now. Nevertheless, Edgeworth's contribution deserves to be recognized.

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Figure Captions

Figure 1. Distributions of semimajor axis, aphelion, cosine (inclination), and argument of perihleion for comets evolved to observable short-period orbits in dynamical simulations by Duncan et al. (1988). Solid curves are for 281 comets in the dynamical simulations; dashed curves are 121 observed short-period comets from Marsden's (1983) Catalog of Cometary Orbits.

Figure 2.. Scatter diagrams in semimajor axis and incliantion for the observed short-period comets (left), for a dynamical simulation of cornets captured to short-period orbits from the Oort cloud (center), and for a dyanrnical simulation of comets captured from a hypothetical comet belt beyond Neptune. From Quinn et al. (1991),

Figure 3. Coronagraphic photograph of the disk of material around the star β Pictoris, viewed edge-on (Smith and Terrile, 1987). Disk material extends out 1,100 AU on either side of the star. The central star and the inner disk is occulted by the instrument, The disk was discovered by the IRAS satellite. Such disks appear to be common around main sequence stars.

Figure 4. Cumulative absolute R magnitude distribution for the 17 discovered Kuiper belt comets (solid curve), and for just the nine objects discovered at R > 40 AU. The diameter scale assumes a cometary albedo of 0.04.

Figure 5, Planet-crossing times as a function Of initial semimajor axis for test particles in the outer planets region as found by Holman and Wisdom (1993). Vertical lines show the time of loss of the first (of 6) test particles at a particular semimajor axis, and dots above the lines show the time of loss for the other particles. Particle orbits were integrated for 8 x 10^8 years between the planets and 2 x 10^8 years beyond Neptune. Long-1ived survivors at the semimajor axis values of each planet are Trojan-type librators around the L_4 and L_5 Lagrange points.

Figure 6, Planet-crossing times as a function of initial semimajor axis for test particles in the trans-Neptunian region (Levison and Duncan, 1993). Particles were removed if they became Neptune-crossing or if they made a close approach to Neptune during the 10^9 period of the numerical integrations. A) initial eccentricity = 0.01; B) initial eccentricity = 0,1.

Figure 7. Radial distribution of test particles in the Kuiper belt after a 4 x 10^9 year integration (Levison and Duncan, personal communication). The initial radial distribution assumes a surface density of planetesimals in the protosolar nebula proportional to $1/r^2$. An initial eccentricity of 0.05 is assumed.

Figure 8. Upper limits on the sky density of Kuiper belt objects as set by various searches (arrows), and the first successful detection (star). The searches are: 'I', Tombaugh (1961); K, Kowal (1989), LJ88, Luu and Jewitt (1988) with Schmidt telescope (S) and CCD (CCD), respectively; LD, Levison and Duncan (1990); CCT, Cochran et al. (1991); TGBH, Tyson et al. 1992; and IJ93, Luu and Jewitt (1993a). The solid circle and arrow at upper right is a predicted limit based on a planned search in 1994 with the Hubble Space Telescope by Cochran, Levison, Stern, and Duncan (personal communication). The dashed lines are power law fits to various model size distributions (see text),

Table 1. Kuiper Belt Objects*

Designation	r AU	a AU	e	i deg	P yr	R mag.	D km
1992 QB_1	41.2	43.83	0.0876	2.213	290.2	22.8	250
1993 FW	42.4	43.93	0.0407	7.745	291.2	22.8	270
1993 RO	32.3	39.70’	0.2046	3.723	250.1	23	140
1993 RP	35.4			2.79		24.5	90
1993 SB	33.1	39.42’	0.3214	2.28	247.5	22.7	170
1993 SC	34.4	39.50’	0.1850	5.164	248.2	21.7	290
1994 ES_2	46.2			0.372		24.3	160
1994 EV_3	44.8			4.80		23.3	240
1994 GV_9	42.2			0.056		23.1	230
1994 JS	36.6			15.4		22.4	240
1994 JV	35.2			18.1		22.4	215
1994 JQ_1	43.4			3.84		22.9	270
1994 JR_1	35.2			3.8		22.5	210
1994 TB	31.7			10.23		21.5	270
1994 TG	42.2			6.76		23	240
1994 TH	40.9			16.07		23	230”
1994 TG_2	41.5			3.86		24	150

* Listed in order of discovery. Data from discovery IAU Circulars, Minor Planet Electronic Circulars, and B. Marsden (personal communication).

+ Tentative orbit. Forced 2:3 resonance solution.

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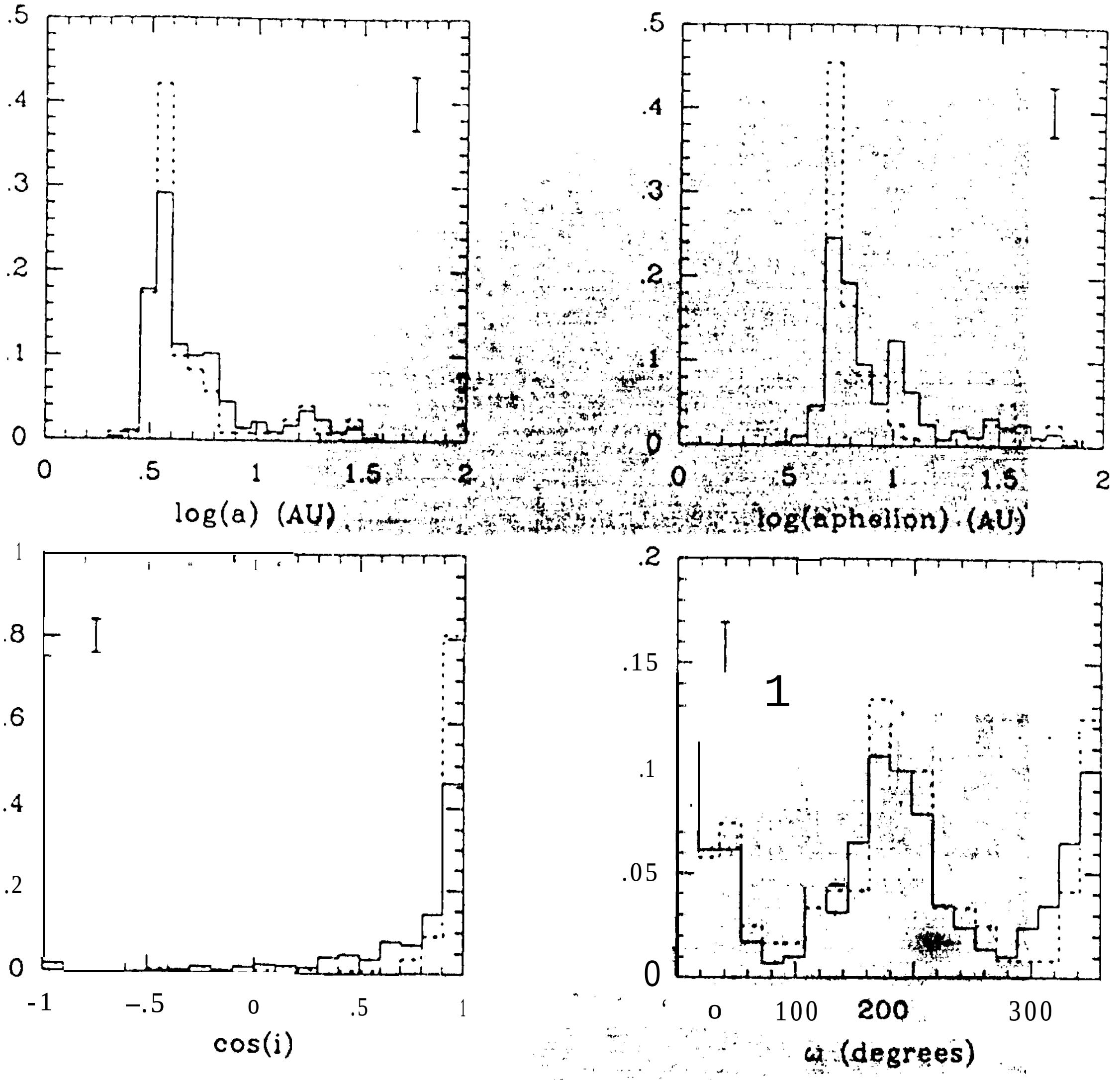

.5
.4
.3
.2
.1
0
0
.5
1
1.5
2
log(a) (AU)
log(aphelion) (AU)
1
.8
.6
.4
.2
-1
-.5
.5
cos(i)
.15
.1
.05
100
200
300
ω (degrees)

Figure 1.

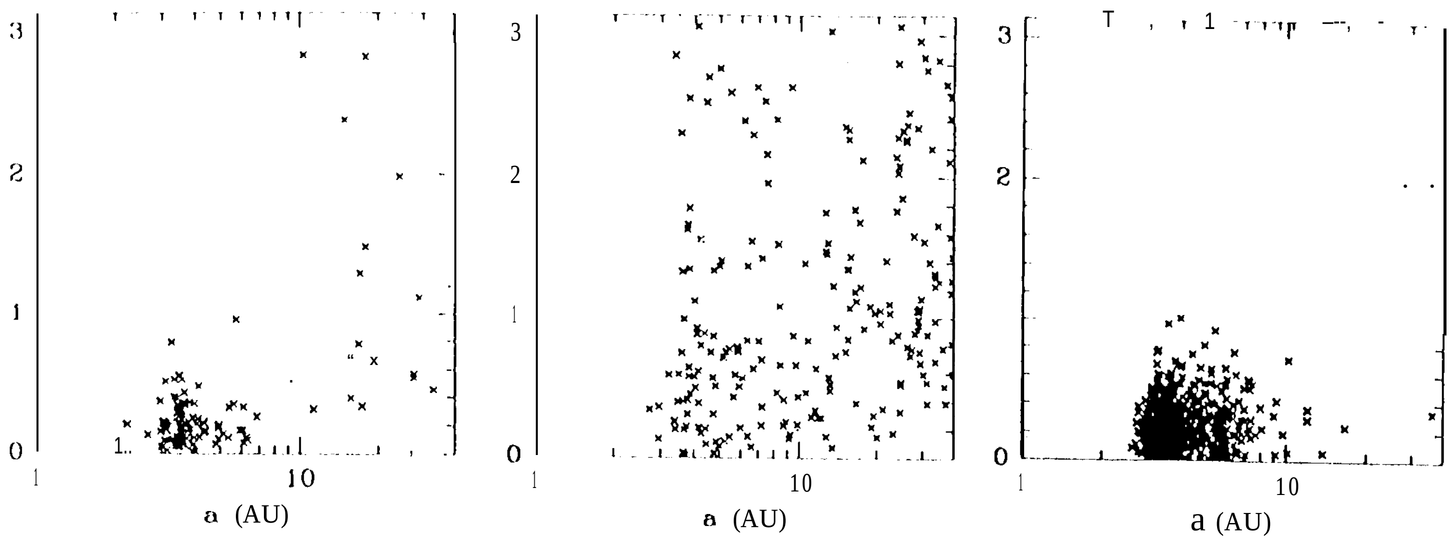


Figure 2.

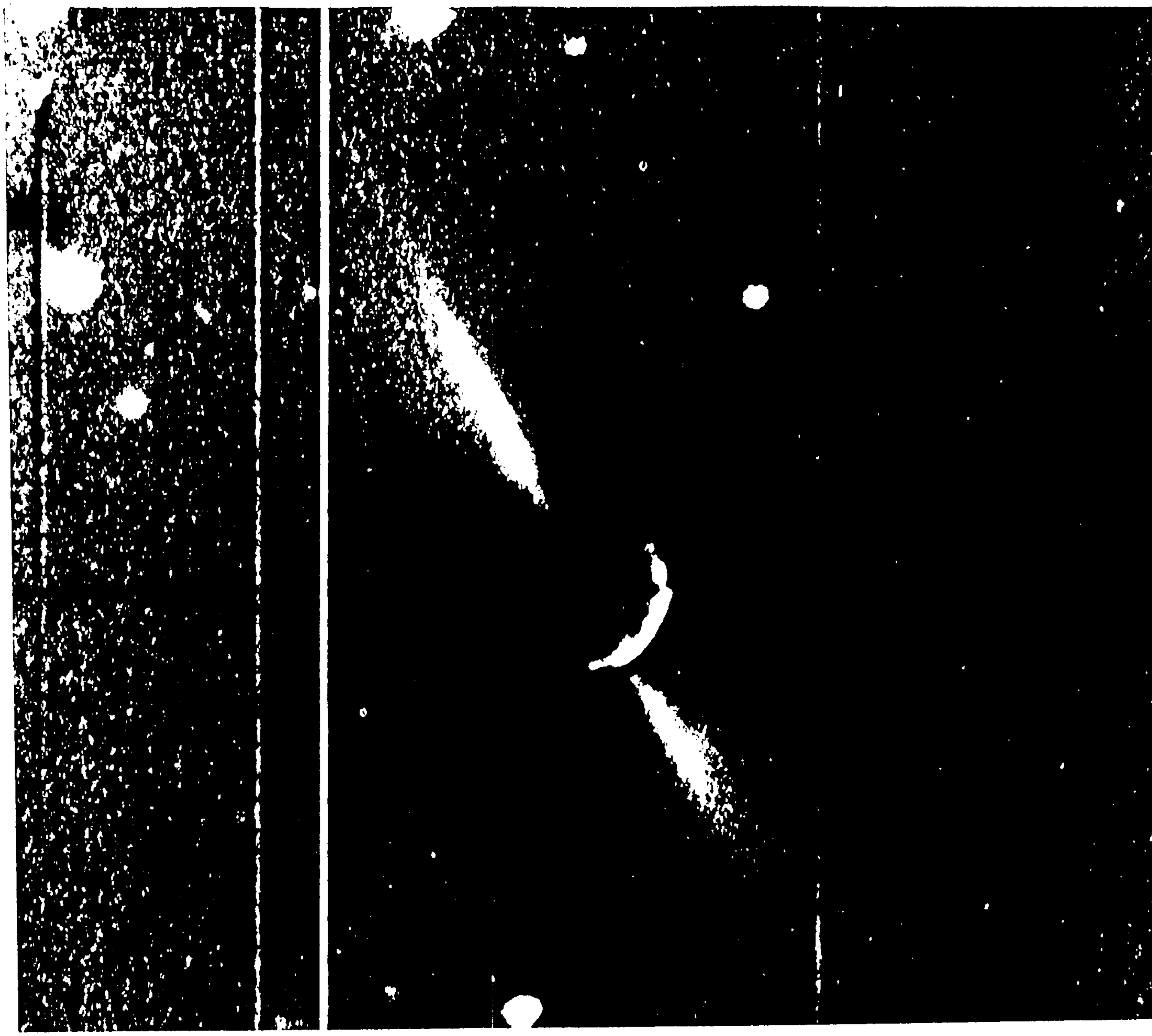
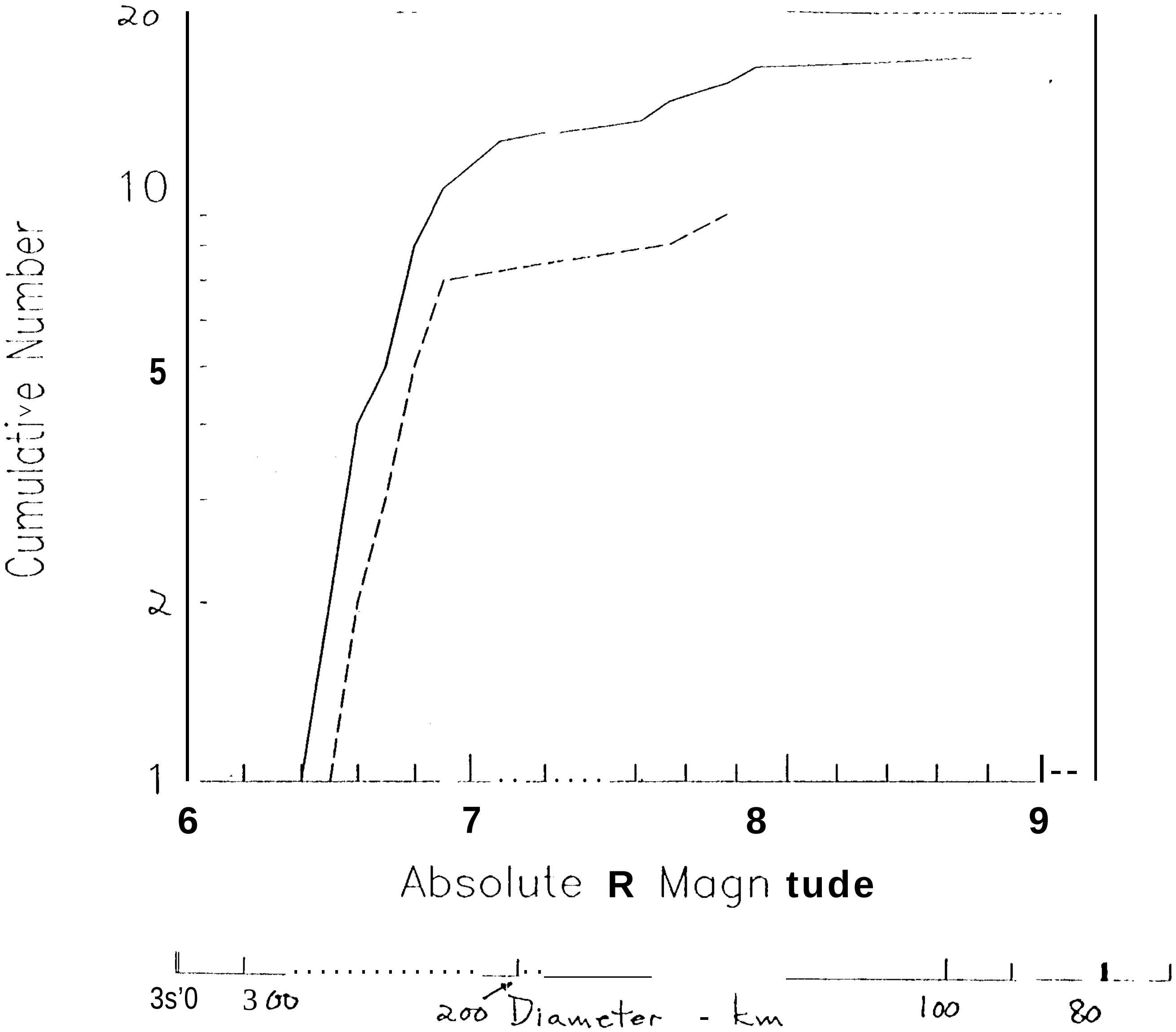
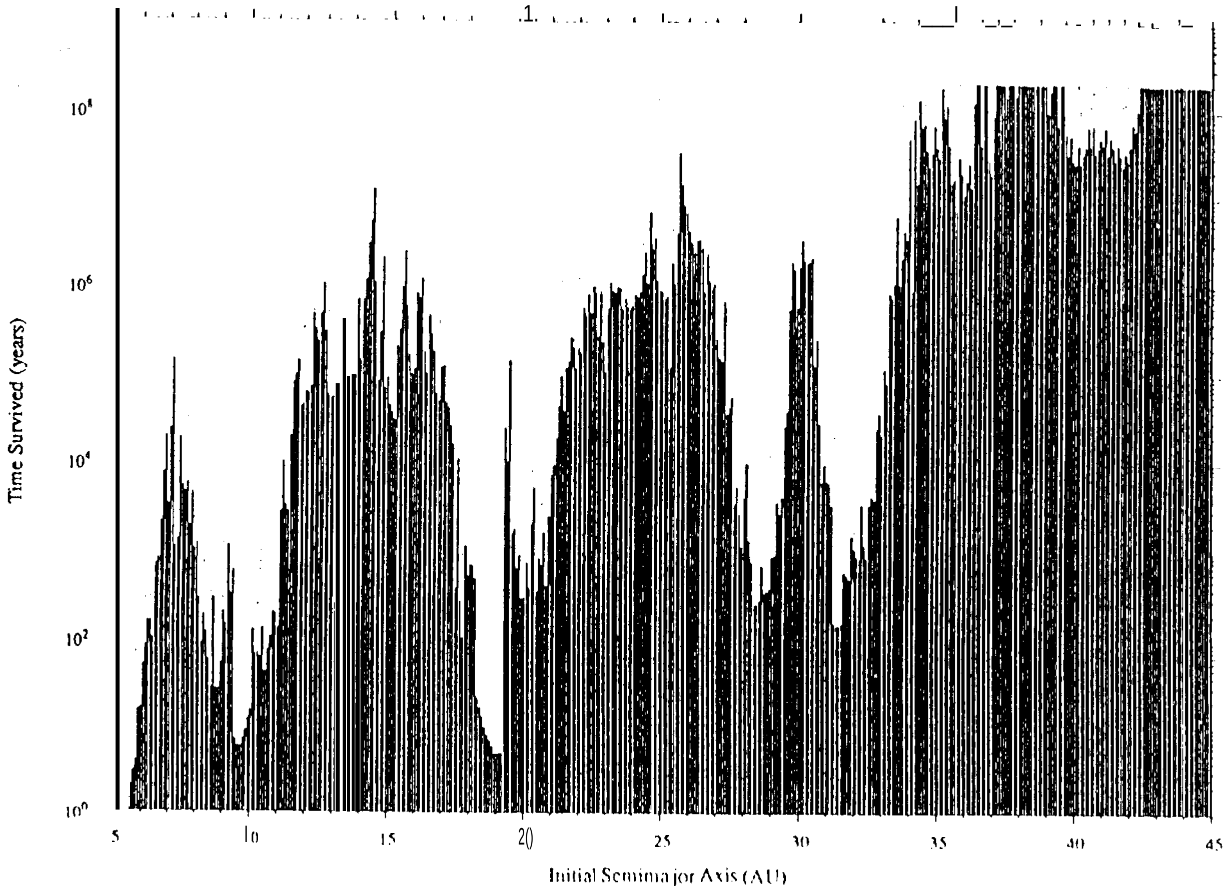


Figure 3.



20
10
5
2
1
Cumulative Number
6
7
8
9
Absolute R Magn tude
3s'0
3 00
200
Diameter - km
100
80

Figure 4.



Time Survived (years)
10^8
10^6
10^4
10^2
10^0
5
10
15
20
25
30
35
40
45
Initial Semimajor Axis (AU)

Figure 5.

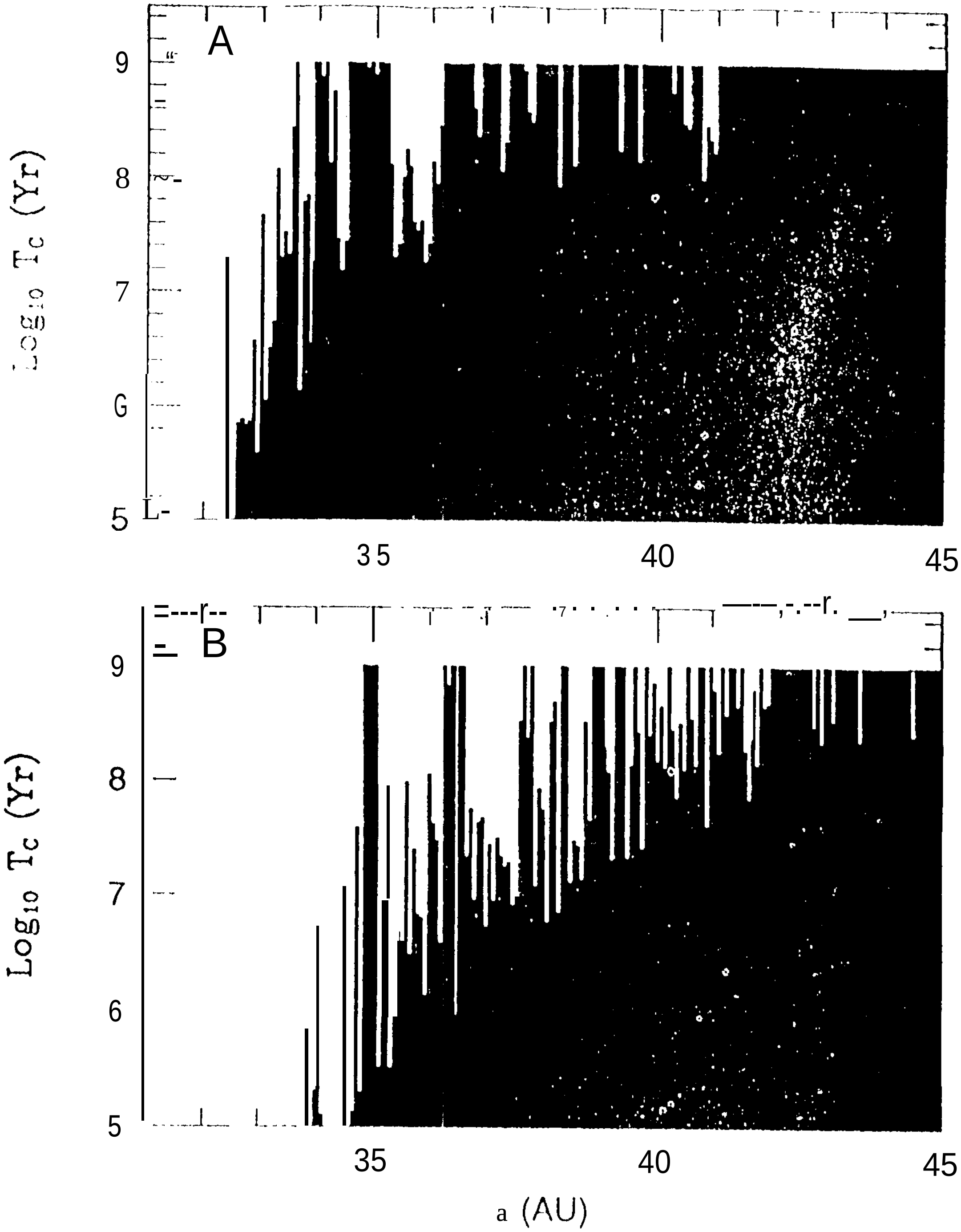
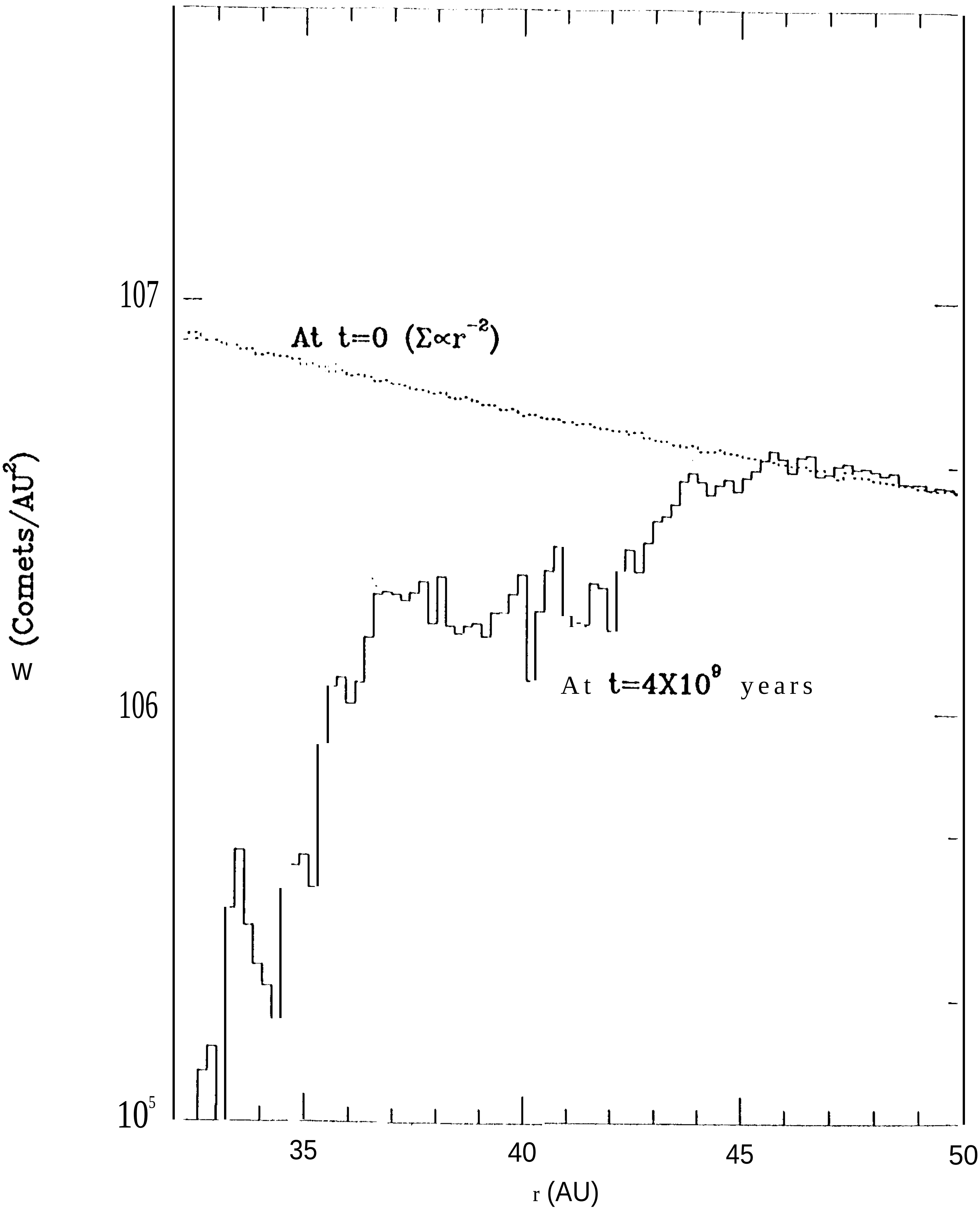
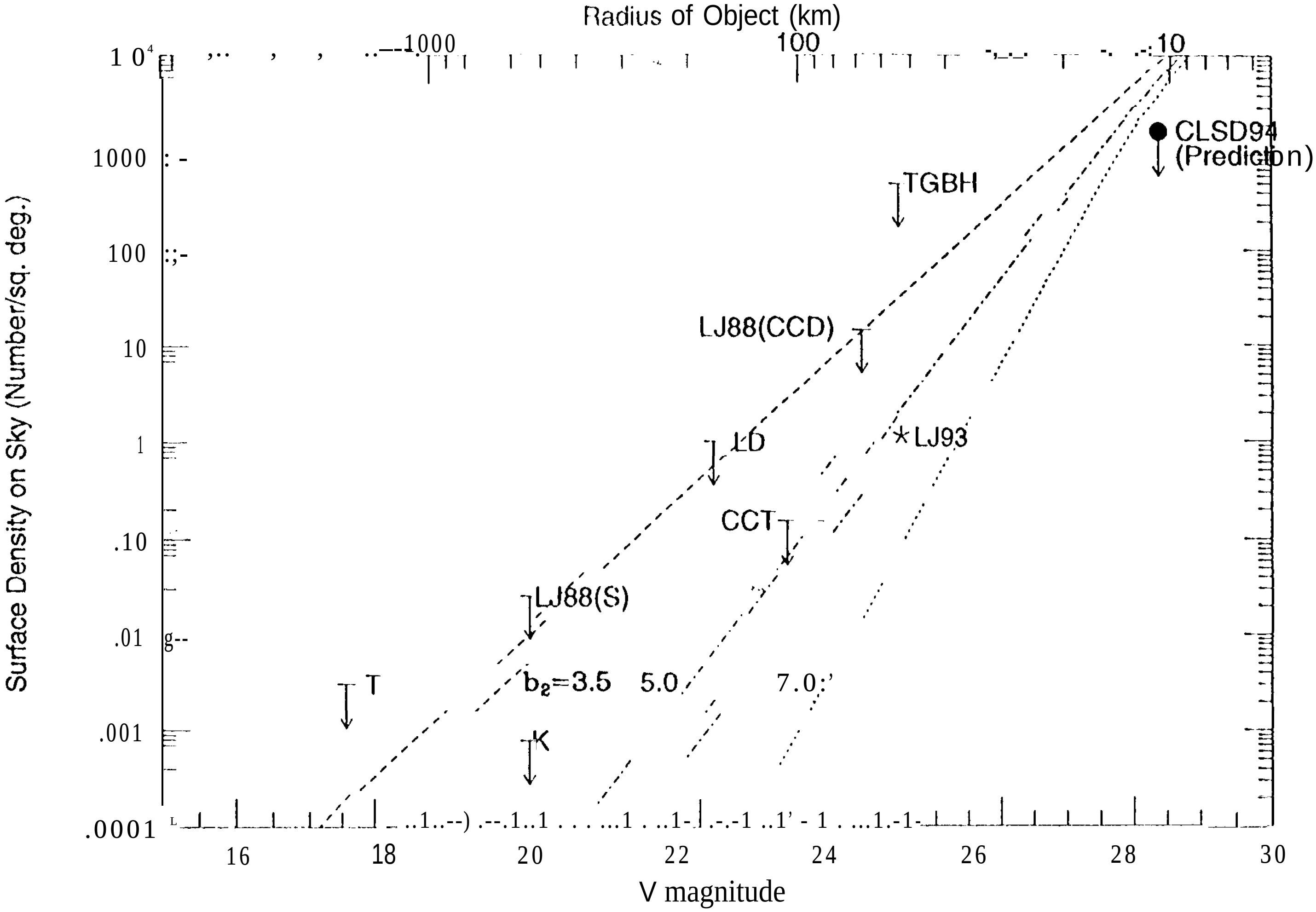


Figure 6.



W (Comets/AU²)
107
106
10⁵
At t=0 (Σ∝r⁻²)
At t=4X10⁹ years
35
40
45
50
r (AU)

Figure 7.



Radius of Object (km)
1000
100
10
CLSD94
(Prediction)
TGBH
LJ88(CCD)
LD
LJ93
CCT
LJ88(S)
T
K
b_2=3.5
5.0
7.0
Surface Density on Sky (Number/sq. deg.)
10^4
1000
100
10
1
.10
.01
.001
.0001
16
18
20
22
24
26
28
30
V magnitude

Figure 8.